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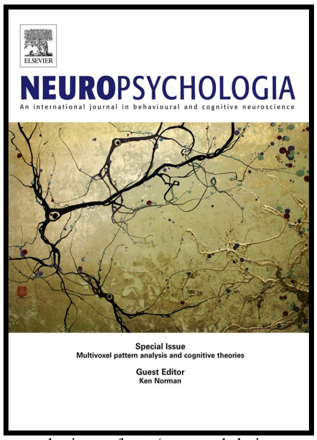

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On the relationship between auditory cognition and speech intelligibility in cochlear implant users: An ERP study

Mareike Finke[1,2*], Andreas Büchner[1,2], Esther Ruigendijk[2,3], Martin Meyer[4,5], Pascale Sandmann[2,6,7]

[1]Department of Otolaryngology, Hannover Medical School, Germany

[2]Cluster of Excellence "Hearing4all"

[3]Department of Dutch, University of Oldenburg, Germany

[4]Neuroplasticity and Learning in the Healthy Aging Brain, Psychological Institute, University of Zurich, Switzerland

[5]Cognitive Psychology Unit (CPU), University of Klagenfurt, Austria

[6]Department of Neurology, Hannover Medical School, Germany

[7]Department of Otorhinolaryngology, University of Cologne, Germany

*Correspondence: Mareike Finke, Hannover Medical School, Carl-Neuberg-Str. 1, 30625 Hannover, Finke.Mareike@mh-hannover.de

Abstract

There is a high degree of variability in speech intelligibility outcomes across cochlear-implant (CI) users. To better understand how auditory cognition affects speech intelligibility with the CI, we performed an electroencephalography study in which we examined the relationship between central auditory processing, cognitive abilities, and speech intelligibility. Postlingually deafened CI users (N=13) and matched normal-hearing (NH) listeners (N=13) performed an oddball task with words presented in different background conditions (quiet, stationary noise, modulated noise). Participants had to categorize words as living (targets) or non-living entities (standards). We also assessed participants' working memory (WM) capacity and verbal abilities. For the oddball task, we found lower hit rates and prolonged response times in CI users when compared with NH listeners. Noise-related prolongation of the N1 amplitude was found for all participants. Further, we observed group-specific modulation effects of event-related potentials (ERPs) as a function of background noise. While NH listeners showed stronger noise-related modulation of the N1 latency, CI users revealed enhanced modulation effects of the N2/N4 latency. In general, higher-order processing (N2/N4, P3) was prolonged in CI users in all background conditions when compared with NH listeners. Longer N2/N4 latency in CI users suggests that these individuals have difficulties to map acoustic-phonetic features to lexical representations. These difficulties seem to be increased for speech-in-noise conditions when compared with speech in quiet background. Correlation analyses showed that shorter ERP latencies were related to enhanced speech intelligibility (N1, N2/N4), better lexical fluency (N1), and lower ratings of listening effort (N2/N4) in CI users. In sum, our findings suggest that CI users and NH listeners differ with regards to both the sensory and the higher-order processing of speech in quiet as well as in noisy background conditions. Our results also revealed that verbal abilities are related to speech processing and speech intelligibility in CI users, confirming the view that auditory cognition plays an important role for CI outcome. We conclude that differences in auditory-cognitive processing contribute to the variability in speech performance outcomes observed in CI users.

Keywords: Cochlear implant, event-related potentials, verbal ability, speech intelligibility, listening effort, electroencephalography

1. Introduction

Cochlear Implants (CIs) bypass a non-functional inner ear by direct electrical stimulation of the auditory nerve. Compared with normal acoustic hearing, sound transmitted through the CI is degraded (Drennan and Rubinstein, 2008). Many CI users develop good speech intelligibility, in particular in quiet background conditions (Krueger et al., 2008). However, in noisy surroundings, the speech understanding typically decreases remarkably in CI users (Hochmair-Desoyer et al., 1997; Wilson and Dorman, 2008; Zeng et al., 2011). In general, there is a high variability in speech recognition ability across CI users which is likely caused by factors related to the implant, the auditory nerve, and the reorganization of the central auditory system (Drennan and Rubinstein, 2008; Nadol et al., 1989; Sandmann et al., 2012, 2015). In particular, electrical hearing may require additional explicit processing due to a mismatch between the attributes of the current CI input and the attributes stored in the long-term memory (Finke et al., 2015; Rönnberg et al., 2013).

Typically, the CI outcome is assessed by speech intelligibility tests in which the patients are examined with monosyllabic words (Hahlbrock, 1953) or sentences, presented either in quiet or in background noise (Hochmair-Desoyer et al., 1997). The score, usually expressed as the percentage of correctly repeated words, is used to draw inferences about the hearing abilities with a CI. However, the behavioral performance reflects the combined effects of different sensory and cognitive processes. It is currently not well understood how variations in speech recognition ability with the CI are related to specific sensory and cognitive processes. By contrast, event-related potentials (ERPs) can provide a continuous measure of neural processing between a stimulus and a behavioral response. With ERPs, different stages of central auditory processing can be discriminated, making it possible to better understand the auditory-cognitive factors contributing to the speech intelligibility in CI users.

Auditory ERPs have been used before to measure speech-sound processing in CI users and in normal-hearing (NH) listeners. Among the long-latency ERPs, the N1-P2 complex seems to be particularly useful to study auditory processing because it can be evoked by a variety of stimuli. Alterations in long-latency ERPs have been reported for subject populations who experience perception difficulties, among them individuals with hearing impairment and CI users (Oates et al., 2002; Sandmann et al., 2009). Moreover, the N1-P2 complex is modulated by background noise. Results from NH listeners have suggested that interrupted or babble noise leads to stronger ERP modulations than continuous noise (Bennett et al., 2012; Billings et al., 2009, 2011; Papesh et al., 2015). It is of clinical interest to understand whether CI users show similar ERP modulations as a function of background noise, and whether the N1-P2 complex can help understand the variability in speech recognition ability with the CI. Thus, in our study we used different types of background noise to compare speech-in-noise encoding and behavioral measures of speech perception between CI users and NH listeners.

Central auditory and cognitive processing in CI users has been usually examined by means of the oddball paradigm (Beynon et al., 2005; Groenen et al., 2009; Henkin et al., 2009). Here, the participants are presented with infrequent stimuli deviating in some physical or higher-order feature from regular standard sounds (Donchin and Coles, 1998; Polich, 2007). Typically, a negative (N2) and a positive (P3) deflection is elicited to task-relevant stimuli over central and parietal scalp regions, respectively (Luck, 2014). Previous studies have reported prolonged P3 latencies in CI users than in NH listeners which has been interpreted as slower stimulus evaluation in CI users (Beynon et al., 2005; Henkin et al., 2009, 2014). Also other late ERP components such as the N2 or the N4 have been associated with access to lexical information and semantic categorization, respectively (Brink and Hagoort, 2004; van den Brink et al., 2001; Deacon et al., 1991; Polich, 1985; Schmitt et al., 2001). Importantly, it is currently not well understood whether these ERPs components are comparable between CI users and NH listeners. Despite providing important insights into central auditory processing, most of the EEG studies with CI users have been limited in that they used simple stimuli such as tones and syllables (Beynon et al., 2005; Groenen et al., 2009; Okusa et al., 1999; Soshi et al., 2014). More complex stimuli have been used only recently in a study with a limited stimulus set consisting of two words (Henkin et al., 2014).

There is increasing evidence that higher-order resources modulate speech perception not only in NH listeners but also in individuals with hearing loss. For instance, verbal WM capacity has been found to relate to speech intelligibility, particularly in adverse listening conditions (Akeroyd, 2008; Lunner, 2009; Rönnberg et al., 2013; Rudner et al., 2008; Zekveld et al., 2007a, 2007b). Also, rhyme judgment and lexical abilities seem to influence speech intelligibility (Akeroyd, 2008; Andersson, 2002; Banks et al., 2015; Benard et al., 2014; Lyxell et al., 1998). Despite being of clinical relevance, it is currently not well understood how verbal WM capacity and other verbal abilities affect speech recognition ability with the CI. Knowing the influence of these cognitive factors would help better understand the high variability in speech intelligibility outcomes observed in CI users.

The current study investigated auditory and cognitive processing of words presented in different background conditions (quiet, stationary noise, modulated noise) and its relationship to cognitive abilities and speech intelligibility in CI users. We examined auditory information computation at lower-level sensory and higher-order processing stages (Mattys et al., 2012), and the interplay between the cortical response at these processing stages and different background conditions. The use of two-syllabic words enabled us to measure the neuronal processes underlying speech perception in relatively natural listening conditions. Similar to previous observations in NH listeners (Bennett et al., 2012; Billings et al., 2009; Papesh et al., 2015), we expected ERP modulations in CI users as a function of background noise. However, given their susceptibility to background noise (Hochmair-Desoyer et al., 1997; Zeng et al., 2011), we hypothesized a different pattern of ERP modulation in CI users when compared with NH listeners. Further, we expected that speech recognition ability with the CI is related to central auditory processing (i.e. ERPs), to verbal WM capacity and to lexical abilities. Observing such relationships would support the view that the CI outcome is influenced by a variety of factors, among them cognitive abilities and the recruitment of the auditory cortex during speech sound processing.

2. Materials & Methods

2.2. Participants

Thirteen postlingually deafened CI users (7 females) and the same number of NH participants (6 females) took part in the present study. All participants had German as mother tongue. Because of the considerable age range across CI users (mean age and standard deviation (SD): 60 ± 10 years; range 43-75 years), each CI user was matched with a NH participant for age (mean age and SD: 59 ± 9.5 years; range 44-74 years). Additionally, groups were matched in terms of years of education; mean years of education and SD for CI: 13.5 ± 3.5 years, range 9.5-21 years; and for NH: 14.5 ± 2.7 years, range 11.5-21 years). All participants had normal or corrected-to-normal vision and no history of neurologic or psychiatric illness. CI users were invited to participate in the study when they had a minimum speech understanding of 20% in the Hochmair-Schulz-Moser (HSM) sentence test in noise (10 dB signal-to-noise ratio; SNR) (Hochmair-Desoyer et al., 1997). All CI users were implanted with a MED-EL FLEX electrode and used the FSP or FS4 speech processing strategy on the tested ear. In case of bilateral implantation, generally the better ear was tested. By mistake one CI user (CI042) was tested with the poorer ear which was implanted more recently. However, his performance on the tested ear was very good (see **Table 1** for more details). Additional statistical results revealed that the exclusion of this CI user and the matched NH participant did not change the results. CI022s speech perception scores were equally well on both ears, and we tested the ear she subjectively preferred.

On average, performance in the HSM sentence test was 88.3% in quiet (SD ± 15%) and 49% (SD ± 21.2%) in noise at an SNR of 10 dB. Eight CI users were unilaterally implanted and five were bilaterally implanted. Because we do not have speech intelligibility scores for the hearing aid ear alone, we report the hearing loss tested by pure tone audiometry for the contralateral ear (unaided). On average, bimodally fitted CI users had a hearing loss of 50 dB at low frequencies (average over 125, 250, and 500 Hz) and 78 dB at high frequencies (average over 1, 2, and 4 kHz). All participants had been using their CI for at least 14 months (mean use and SD: 30 ± 15.5 month; range 14-58 month) before the experiment, and none of the CI users used sign language to communicate. **Table 1** provides the details about the CI system, the speech processor, and the clinical history of each CI user. All CI users received the auditory stimulation via an audio cable. Each NH participant was tested at the same ear as their match in the group of CI users. Their normal hearing was verified by pure tone audiometry which revealed ≤ 20 dB mean hearing loss (individual mean over the tested frequencies 500-4000Hz) in the tested ear. In total, 2 right ears and 11 left ears were tested in each group. Participants gave informed written consent before the experiment. The experimental protocol was approved by the Ethical Committee of the Hannover Medical School and was in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

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2.3. Task & Procedure

Participants were tested with an auditory oddball paradigm (Polich, 2007; Polich et al., 1997). The probability of targets was p = 0.2 and of nontargets p = 0.8. Each trial consisted of a two-syllabic German noun (~ 800 ms length) which had to be classified as a living or non-living entity. We used a selection of the stimuli Rufener and colleagues used in a previous study (Rufener et al., 2014). Targets were defined as words describing living entities such as persons or animals. Participants were asked to semantically classify the words and press a button with their thumb whenever they heard a target word. The response window had a duration of 1700 ms. Words were presented in pre-defined lists. Each list consisted of seven target words and 28 nontarget words which were pseudo-randomly repeated ten times. The only constraint was that targets were not presented consecutively but were separated by at least two nontargets. In total, 70 targets were presented for each word list. Participants were tested in three background conditions (**Figure 1**). Words were presented in quiet or in background noise (10 dB SNR). The background could be either stationary (CCITT; (Zwicker and Fastl, 2013)) or modulated noise (ICRA5; (Dreschler et al., 2001)). Importantly, the stationary CCITT noise presented in the oddball paradigm was the same as used in HSM sentence test in noise (Hochmair-Desoyer et al., 1997), which allowed a direct comparison between task performance in the oddball paradigm and the score assessed by a clinical speech test. The order of the three conditions was randomized across participants. Importantly, we designed three different word lists containing different stimuli. As a consequence, each person was tested with different stimuli in each background condition to avoid training effects. EEG recording lasted ~ 45 minutes plus breaks.

The assignment of a word list to a certain background condition was randomized across participants. For each word list, target and nontarget stimuli were matched regarding word frequency according to the "Leipziger Korpus" (http://wortschatz.uni-leipzig.de/). We also kept the morphological complexity constant by balancing the amount of derived and non-derived words in the two stimulus classes. Since neuroimaging studies (specifically MEG, see (Zweig and Pylkkänen, 2009)) have shown specific effects for morphological complexity, we also kept morphological complexity of our items constant by balancing the relative amount of derived and non-derived words in the two stimulus classes. Derivation is the process with which new words can be made by adding a prefix or suffix to a word, e.g. in English, with the suffix '-er' we can create a noun from a verb stem: to swim and swimmer. Derived words hence are more complex than non-derived words, in that they can be decomposed in parts unlike non-derived words, such as mother[1]. In German, the stress assignment to the penultimate syllable is supposed to be the default stress pattern (Eisenberg, 2009; Féry, 1998; Wiese, 2000). All words used in the present study are stressed on the penultimate syllable.

Prior to the EEG recording, participants completed three tests that assessed the verbal working memory and other verbal abilities, in particular verbal fluency and word recognition ability (see the next section for more details about these tests). This was motivated by fact that previous studies have found these cognitive measures to be diminished in different populations of hearing aid and CI users, and some of these studies have found a relationship between these measures and speech intelligibility (Kronenberger et al., 2013a, 2013b, 2014; Lyxell et al., 1998; Rönnberg et al., 2013). The selection of non-auditory tests followed the principle of minimizing effects of audibility and auditory spoken language processing (Kronenberger et al., 2013b). Therefore, all of the cognitive tests applied in the current study do not rely on auditory input but on visual input or self-produced items.

We used the "Mehrfachwahl-Wortschatz-Intelligenz-Test" (MWT-B) which is a vocabulary-intelligence test that measures how well participants recognize words on the basis of the written word form (Lehrl, 1999). In this test, participants have to choose the existing word from a list of five options, with one word being a real word. Regarding the verbal fluency test, we applied the sub-test "lexical fluency" from the "Regensburger

[1] Since it is very hard to find enough words of similar frequency of use for both classes (living and non-living) anyway, we could not simply use non-derived or derived words only.

Wortflüssigkeitstest" (RWT;(Aschenbrenner et al., 2000). Here, the participants' task was to report as many nouns starting with the letter "S" as possible within two minutes. Importantly, for the RWT age-based norms are available. Verbal WM capacity was measured by means of a German version of the size-comparison span (SICSPAN) test developed by Sörqvist and colleagues (Sörqvist et al., 2010). The three tests had a total duration of ~20 minutes.

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2.4. Data recording and analysis

2.4.1. Verbal ability data and listening effort

The MWT-B and the RWT were analyzed according to the official guidelines provided with the test material. For statistical analyses, the individual percentile in relation to the norm sample was used, as this was available for both tests. The results of the SICSPAN test were analyzed in two different ways, in particular by taking the total sum of remembered words and by counting the maximum amount of remembered items within one block.

In addition to the psychometric tests, participants rated their subjective listening effort in the three background conditions during EEG recording. In recent years, the concept of listening effort became the umbrella term for cognitive load in adverse listening conditions (Zekveld et al., 2010; Rönnberg et al., 2013). Several studies used the pupil response as an objective measure of listening effort (Koelewijn et al., 2015, 2012; Lunner et al., 2009; Zekveld et al., 2010). However, it is likely that also endogenous ERP components can be indicators of listening effort. In order to explore this relationship, the participants performed a subjective rating of the listening effort for each background condition. Specifically, the participants marked their effort to understand the words on a 5-point scale ranging from "Not difficult at all" (1) to "I cannot understand the words" (5).

2.4.2. Behavioral data

For behavioral analysis, a correct trial was defined as a correct button press that occurred between 100 ms and 1700 ms after target word onset. Response times (RTs) as well as hit rates were analyzed (**Figure 2**) using two separate repeated-measures 2x3 ANOVAs, with the between-subjects factor 'Group' (CI, NH) and the within-subjects factor 'Background' (quiet, stationary noise, modulated noise). The Greenhouse-Geisser correction was applied whenever the sphericity assumption was violated. Significance was determined at an alpha level of 0.05 for all analyses, and partial eta square is reported as a measure of effect size.

2.4.3. Electrophysiological data: Recording and data processing

EEG was continuously recorded by a SynAmps amplifier (Neuroscan, Compumedics, Charlotte, NC) from 81 scalp electrodes using a 128-channel Quik-Cap (Neuroscan, Compumedics, Charlotte, NC). The electrodes were placed according to the 10-10 system. Over parietal scalp regions seven additional electrodes were used to have more information from scalp regions where we expected task-related (P3) effects. Two additional electrodes were placed at the left and the right mastoid. The common reference electrode was placed at the tip of the nose. Moreover, eye movements were measured with two bipolar electrodes placed above and below the right eye (vertical electrooculogram), and two bipolar electrodes placed at the outer chanthi of each eye (horizontal electrooculogram). The EEG was recorded at 1 kHz without online bandpass-filtering using the software Curry Neuroimaging Suite 7 (Neuroscan, Compumedics, Charlotte, NC). Electrode impedances were kept below 20 kOhms during the whole recording session.

EEG data were analyzed with MATLAB 8.1.0.604 (R2013a; Mathworks, Natick, MA) and EEGLAB 12.0.2.5b (Delorme and Makeig, 2004). The raw data were resampled to 500 Hz, offline filtered from 1 to 40 Hz using sinc FIR filters windowed with a Hanning window (Widmann and Schröger, 2012), and epoched into segments from 0 to 2000 ms relative to auditory stimulus onset. The data were then pruned of unique, non-stereotype artifacts (threshold: 3 standard deviations (SD)). Subsequently, an infomax independent component analysis (ICA) was computed (Bell and Sejnowski, 1995). The resulting ICA weights were then applied to filtered (0.1 – 30 Hz) and epoched (-200 to 1500 ms relative to stimulus onset) raw data. Independent components reflecting eye-blinks, horizontal eye movements, electrical heartbeat activity and CI artifacts were removed (Jung et al., 2000a, 2000b). Components representing CI artifacts were identified by the centroid on the side of the implanted device and by the time course of component activity (for details about the reduction of CI artifacts by means of ICA see (Debener et al., 2008; Sandmann et al., 2009; Viola et al., 2011)). After removal of artifact-related ICA components, channels which were missing due to the speech processor and transmitter coil were interpolated. Here, we used spherical spline interpolation (mean number of missing electrodes: 8; SD: 2.4; range: 4 – 11; (Perrin et al., 1989)). Only correct trials (hits for target stimuli; correct rejections for nontarget stimuli) were included for further analyses. Auditory ERPs to targets and nontargets were obtained by time-domain averaging. The pre-stimulus interval (-200 to 0 ms) was used for baseline correction. In these averages, 75.4% (SD: 13.8) and 88.1% (SD: 4.8) of the epochs were included for the CI users and for the NH listeners, respectively.

ERP analysis was performed on the single-subject averages for a frontocentral (N1 and P2 peak), a central (N2 peak), and a parietal (P3 peak) region-of-interest (ROI), including 13 (N1, P2) or 15 (N2, P3) channels (see **Figures 3, 4** and **5** for the exact positions of the channels). The corresponding ROIs included the channels with the largest deflections observed in the grand average (computed across all conditions) of NH listeners and CI users. Following recommendations (Luck, 2014), the quantification of the ERP amplitude was done by means of the signed area, that is, by computing the positive (P2, P3) and the negative (N1, N2) area under the ERP waveform over a given latency range (N1: 50-200ms; P2: 120-400ms; N2: 300-850ms; P3: 500-1200ms). In general, latency ranges for ERP amplitude and latency detection were defined on the basis of the grand average computed across all conditions and participants. The ERP latency was quantified by means of the 50% area latency measure. This was done by computing the signed area under the ERP waveform over a given latency range and then finding the time point that divides that area into one-half. The use of the area amplitude and latency measures is advantageous to the more conventional peak amplitude measure because it is a linear measure that is not influenced by single-trial latency jitter and which is relatively insensitive to high-frequency noise (Luck, 2014; Meyer et al., 2011; Petermann et al., 2009).

On the descriptive level, the N2 waveforms of CI users showed a different morphology when compared with NH listeners (**Figure 4**). Given the lack of in-depth reports of N2 ERPs in CI users, we wanted to further explore the morphological differences between CI users and NH listeners. Thus, in addition to N2 peak and latency measures, we used supplementary measures to quantify the difference between the two groups of participants. Specifically, we computed the onset and offset latency of the N2 peak by using the 25% (onset latency) and 75% (offset latency) area latency measure. Afterwards, the width of the N2 peak was calculated by subtracting the offset latency from the onset latency. We also quantified the magnitude of change in the transition from the P2 peak to the N2 peak by computing the linear slope between these two peaks [b = (N2 area amplitude – P2 area amplitude)/ (N2 area latency – P2 area latency)]. These four measures (onset latency, offset latency, width of N2 peak, P2-N2-slope) were compared between CI users and NH listeners by means of independent samples t-tests.

Statistical analysis of all peaks (N1, P2, N2, P3) focused on the respective ROIs (frontocentral: N1, P2; central: N2; parietal: P3). Regarding later stages of neuronal processing (P3), statistical analysis was performed on the difference waveforms which were computed by subtracting the responses to the nontargets from the targets, separately for each background condition (quiet, stationary noise, modulated noise). This was done because specifically the late brain response evoked by the *onset* of the current stimulus (P3 peak) and brain response evoked by the *offset* of the current stimulus (N1 and P2 peak; around 1000 ms after stimulus onset) partly overlapped, at least in CI users who showed prolonged higher-order processing (P3 peak in CI users: around 900 ms after stimulus onset). This overlapping offset response was subtracted in the target-minus-nontarget difference waves, allowing the study of brain activity specifically related to stimulus categorization at P3 latency.

Area amplitudes and latencies of the N1, P2, and N2 ERP were subjected to separate repeated-measures ANOVAs, with Background (quiet, stationary noise, modulated noise) and Targetness (targets, nontargets) as within-subjects factors and Group (CI, NH) as between-subjects factor. Area amplitude and latency measures of the P3 ERP were analyzed by means of separate 3(Background) x 2(Group) ANOVAs.

In general, significant main effects and interactions ($p < 0.05$) in the ANOVAs were followed-up with post-hoc t-tests (Holm-Bonferroni correction; (Holm, 1979), and the Greenhouse-Geisser correction was applied to compensate for violations of the sphericity assumption. Additionally, the partial eta square was used as a measure for effect size, and only (original) p-values passing the Holm-adjusted p-thresholds are reported (Aickin and Gensler, 1996).

3. Results

Table 2 gives an overview over the ANOVA results obtained in the present study. The analyses include the factors Background (quiet, stationary noise, modulated noise) and Targetness (targets, nontargets) as within-subjects factors and Group (CI, NH) as between-subjects factor. As the subjectively rated listening effort was analyzed with non-parametric tests, no F-values but Chi-Square and the Z-value are given.

Table 2 Overview of the ANOVA results[2]

		Main Effect		Interaction Effect
	Background	Group	Target	Background by

[2] *** $p \leq 0.001$; ** $p \leq 0.01$; * $p \leq 0.05$; n.s. = not significant

				Group
Response Times	n.s.	F = 5.243*	Not applicable	n.s.
Hit Rates	n.s.	F = 38.054 ***	Not applicable	n.s.
Listening Effort	Chi-Square = 12.426**	all Z < 2.799**	Not applicable	n.s.
N1 amplitude	F = 6.549**	n.s.	F = 36.944***	n.s.
N1 latency	F = 116.578 ***	n.s.	F = 7.916 ***	F = 21.167***
P2 amplitude	F = 6.762**	n.s.	F = 6.984*	n.s.
P2 latency	F = 4.764*	n.s.	n.s.	n.s.
N2 amplitude	F = 4.111*	n.s.	F = 52.704***	n.s.
N2 latency	F = 15.202***	F = 30.032***	n.s.	F = 5.106*
P3 amplitude	n.s.	n.s.	Not applicable	n.s.
P3 latency	n.s.	F = 7.123*	Not applicable	n.s.

3.2. Verbal abilities and listening effort

First, we compared the results of the three behavioral tests assessing the cognitive abilities (MWT-B, RWT and SICSPAN). Regarding the word recognition ability (MWT-B), NH listeners performed significantly better (percentile rank; PR) in distinguishing real words from pseudowords ([$t(24) = -5.291$; $p < .001$]; CI: PR = 50; NH: PR = 90). Regarding the verbal fluency (RWT) and the verbal WM (SICSPAN) both groups performed on par (both $p > 0.092$).

We used Mann-Whitney U tests to compare the subjective listening effort rated by the CI users and the NH participants (**Table 1**). For all background conditions, CI users subjectively rated the listening effort significantly higher than NH listeners (all $p \leq .007$). A Friedman's analysis of variance by ranks revealed significant differences in the listening effort between the three background conditions ($p = .002$). Paired comparisons using Wilcoxon signed-rank tests uncovered that the modulated ($p = .001$) was rated significantly more effortful compared with the quiet background. The difference between the stationary and the quiet/modulated background was not significant ($p > 0.7$).

3.3. Behavioral results of the oddball task

Mean response times (RTs) and hit rates for the three background conditions are displayed in **Table 1** and **Figure 2** for both the CI users and the NH participants. The 3(Background) x 2(Group) ANOVAs revealed significantly prolonged RTs in CI users compared with NH participants, as indicated by a significant main effect for Group [$F(1,24) = 5.580$; $p = .027$; $\eta p^2 = 0.19$]. A main effect for the factor Group indicated significantly lower hit rates in CI users compared with NH participants [$F(1,24) = 38.054$; $p < .001$; $\eta p^2 = 0.61$]. We further analyzed the RTs in three bins (first, second, and third part of the RTs across the experiment) to check for possible group-specific training effects. In addition to the known main effect for group, the 3(Background) x 3(Bins) x 2(Group) ANOVA revealed a significant main effect for Bin for all participants [$F(1,24) = 26.833$; $p < .001$; $\eta p^2 = 0.528$].

We found no effect of Background, neither regarding the RTs nor the hit rates.

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3.4. Event-related potentials

The next sections describe our observations of how these peaks were modulated by the factors Targetness (target word, nontarget word) and Background (quiet, stationary, modulated) in the two groups of participants (CI, NH). The results of the analysis are illustrated in Table1, **Figure 3** (N1, P2), **Figure 4** (N2) and **Figure 5** (P3).

Auditory sensory processing (N1 and P2)

Figure 3 shows the ERPs of NH listeners and CI users at frontocentral scalp regions. The 3(Background) x 2(Targetness) x 2(Group) ANOVAs revealed for the N1 area amplitude and the N1 area latency a significant main effect of Background [amplitude: $F(2,48) = 6.549$; $p = .003$; $\eta p^2 = 0.214$; latency: $F(2,48) = 116.578$; $p < .001$; $\eta p^2 = 0.829$]. There was a significant increase in N1 area latency from quiet to stationary to modulated background and significantly enhanced N1 area amplitude for the quiet and stationary background compared to the modulated background (all $p < 0.007$).

Interestingly, the 3(Background) x 2(Group) ANOVA revealed a significant Background by Group interaction effect for the N1 area latency [$F(2,48) = 21.167$; $p < .001$; $\eta p^2 = 0.469$. Comparing the N1 area latency between the different background conditions within each group confirmed the increase of N1 area latency from quiet to stationary to modulated background (CI: all $p < 0.05$; NH: all $p < .001$). Furthermore, CI users had prolonged N1 latencies in the quiet condition ($p = .001$) but not in noise.

In addition, we found a significant main effect of Targetness [amplitude: $F(1,24) = 36.944$; $p < .001$; $\eta p^2 = 0.606$; latency: $F(1,24) = 7.916$; $p = .001$; $\eta p^2 = 0.248$]. These main effects were due to enhanced area amplitude and shorter N1 area latency for targets than nontargets.

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The results of the P2 peak analysis are given in **Figure 3**. The 3(Background) x 2(Targetness) x 2(Group) ANOVAs for the P2 revealed a significant main effect for

Background for the P2 area amplitude and latency, [amplitude: $F(2,48) = 6.762$; $p = .003$; corrected; $\eta p^2 = 0.227$; latency: $F(2,48) = 4.764$; $p = .013$; corrected; $\eta p^2 = 0.166$]. Comparing the different background conditions revealed smaller P2 area amplitude for the two noise conditions when compared with the quiet condition (both $p < 0.015$). This suggests that background noise reduces the P2 response in both the CI users and the NH listeners. The area amplitude also revealed a significant main effect for Targetness [amplitude: $F(2,48) = 52.704$; $p < .001$; corrected; $\eta p^2 = 0.225$].

Higher-order processing (N2 and P3)

Figure 4 shows the ERPs of NH listeners and CI users at central scalp regions. Detailed results about the quantification of the N2 peak (onset latency, offset latency, width of N2 waveform, P2-N2-slope) are given in **Table 3**. Onset latency refers to the 25% area latency measure, and offset latency refers to the 75% area latency measure. The width of the N2 waveform was quantified by subtracting the N2 offset latency from the N2 onset latency. The magnitude of change from the P2 to the N2 peak was analyzed by computing the linear slope (b = [N2 peak – P2 peak]/[N2 latency – P2 latency]).

Table 3: Quantification of the N2 waveform

	NH Listeners			CI users		
	Quiet	Stationary	Modulated	Quiet	Stationary	Modulated
Onset latency	436 ± 11 ms	449 ± 13 ms	449 ± 12 ms	465 ± 17 ms	553 ± 14 ms	531 ± 24 ms
Offset latency	603 ± 22 ms	593 ± 18 ms	610 ± 24 ms	670 ± 14 ms	714 ± 13 ms	694 ± 17 ms
Δ latency	167 ± 18 ms	144 ± 12 ms	161 ± 17 ms	205 ± 19 ms	161 ± 20 ms	163 ± 19 ms
P2-N2 slope	-4.1 ± 0.4 µV	-4.1 ± 0.4 µV	-3.5 ± 0.4 µV	-3 ± 0.4 µV	-2.2 ± 0.3 µV	-2.4 ± 0.4 µV

The 3(Background) x 2(Targetness) x 2(Group) ANOVAs revealed for the N2 area amplitude and latency a significant effect for Background [amplitude: $F(2,48) = 4.111$; $p = .022$; $\eta p^2 = 0.146$; $F(2,48) = 15.202$; $p < .001$; $\eta p^2 = 0.388$].

Regarding the N2 area latency, we found a significant main effect of Group [$F(1,24) = 30.032$; $p < .001$; $\eta p^2 = 0.556$] and a significant interaction between Background and Group [$F(2,24) = 5.106$; $p = .01$; $\eta p^2 = 0.175$]. Post-hoc t-tests revealed longer N2 area latency in CI users than in NH listeners for all background conditions [all $p < .001$]. Similarly, the latency of the onset (25% area latency) and the offset responses (75% area latency) of the N2 peak was prolonged in CI users when compared with NH listeners [all background conditions: $p \leq$

.003]. Further, post-hoc t-tests revealed that CI users had shorter N2 area latency for quiet when compared with the two noise conditions (both $p < .001$), indicating that background noise prolongs N2 area latency in CI users. By contrast, in NH listeners no condition differences were found ($p > 0.09$). We also analyzed the linear P2-N2 slope from the P2 peak to the N2 peak in NH listeners. The 3(Background) x 2(Targetness) x 2(Group) ANOVAs revealed that in CI users a significant main effect of Group [$F(1,24) = 6.562$; $p < .017$; $\eta p^2 = 0.215$] with steeper slopes for NH participants compared to CI users. Also, this ANOVA revealed significant main effects for Targetness [$F(1,24) = 22.284$; $p < .001$; $\eta p^2 = 0.481$] and for Background [$F(1,24) = 8.071$; $p = .001$; $\eta p^2 = 0.252$]. This suggests different ERP morphology between NH listeners and CI users, particularly during the transition from the P2 peak to the N2 peak.

Also, there was a significant main effect of Targetness [$F(1,24) = 52.704$; $p < .001$; $\eta p^2 = 0.687$] which was due to enhanced N2 area amplitude to targets than to nontargets.

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Figure 5 shows the ERPs of NH listeners and CI users at parietal scalp regions. Given the partial overlap of onset and offset responses at P3 latency, peak analysis was performed on the target-minus-nontarget difference wave (in both groups). The 3(Background) x 2(Group) ANOVAs revealed for the P3 latency a significant effect of group [$F(1,24) = 7.123$; $p = .0013$; $\eta p^2 = 0.229$] which was due to longer P3 latency in CI users than in NH listeners.

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3.5. Correlational analyses

We correlated the three tests accessing verbal abilities with the HSM sentence test (in noise; 10 dB SNR) and the monosyllabic word test (in quiet) to better understand how verbal abilities and verbal working memory relate to speech intelligibility in CI users. **Figure 6** shows the results of this analysis. We found a trend towards significant positive correlations between the RWT scores (verbal fluency) and the HSM sentence test [$r(11) = .518$, $p = 0.061$] as well as with the monosyllabic word test [$r(11) = .536$, $p = 0.059$]. Moreover, we observed associations between central auditory processing, verbal abilities and speech intelligibility with a CI (Figure 6). In particular, we found that the N1 latency (averaged across targets, nontargets and background conditions) was negatively correlated with the lexical fluency [r(11) = -.675, p =.011], with the monosyllabic words test [r(11) = -.625 , p =0.22], and the SICSPAN [r(11) = -.731, p = .005]. The shorter the CI users' N1 latency, the better were their verbal abilities and speech perception in the monosyllabic words test. However, there was no systematic relationship between the degree of hearing loss in the contralateral ear (low/high frequency range) and behavioral or ERP measures across all conditions, suggesting that the influence of hearing loss on the current results was negligible.

As we found a significant Group x Background interaction for the N2 latency, we were interested in how the N2 latencies for the quiet and stationary noise background are related to the scores measures by clinical speech tests (monosyllabic words test and HSM sentences in noise). We found significant negative correlations in both background conditions [quiet: r(11) = -.717, p =0.006; stationary noise: r(11) = -.650, p =0.16], suggesting that shorter N2 latencies are associated with better speech intelligibility with the CI.

In a last step, we analyzed the relationship between the subjective listening effort for each background condition and the respective N2 latency using nonparametric Spearman's rho correlations. We found significant positive correlations for all background conditions in CI users [quiet: r(10) = .579, p =.049; stationary noise: r(9) = .768, p =.006; modulated noise: r(11) = .575, p =0.040] but not for NH listeners.

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4. Discussion

The present study examined the relationship between neural processing of words presented in three different background conditions, verbal abilities, and speech intelligibility in postlingually deafened CI users. In contrast to previous studies (Beynon et al., 2005; Groenen et al., 2009), our participants could not rely on perceptual discrimination alone but had to identify the meaning of the two-syllabic words. Our results revealed poorer speech intelligibility in CI users than in NH listeners and group-specific modulation effects of ERPs as a function of background noise. While NH listeners showed stronger noise-related modulation of N1 latency, CI users revealed enhanced modulation effects of N2 latency. We also observed slower higher-order processing (N2, P3) in CI users than in NH listeners. Finally, correlation analyses revealed that speech intelligibility in CI users is related to ERP measures, lexical abilities, verbal working memory, and subjective listening effort.

Behavioral results

The behavioral results showed lower hit rates and prolonged RTs in CI users compared with NH listeners. This is consistent with previous observations of poorer auditory discrimination ability in CI users than in NH listeners (Sandmann et al., 2015). Impaired performance with a CI may be related to the implant, for instance the limited spectral and temporal information transmitted by the CI, and the spread of electrically evoked neuronal excitation in the cochlea (Drennan and Rubinstein, 2008). In addition, factors related to the peripheral structure (e.g. small amount of surviving spiral ganglion cells) and visual-to-auditory cross-modal reorganization are likely to limit performance outcome with a CI. It seems that limitations in electrical hearing become particularly evident in difficult listening situations, such as speech in noisy background conditions (Hochmair-Desoyer et al., 1997; Zeng et al., 2011). Increased ratings of listening effort in CI users compared to NH listeners strengthen this interpretation.

In contrast to our expectations, we observed no effect of background noise on behavioral performance in the oddball task, neither for the NH listeners nor for the CI users. The present null effect may be caused by the fact that the increase in task difficulty due to additional background noise was too weak to impair speech intelligibility. We speculate that a decrease of SNR in the presented words with background noise (e.g. from 10 dB to 0 dB) would have increased the task difficulty and may have caused a background effect on behavioral level (Bertoli and Bodmer, 2014, 2015). Importantly, all participants rated the modulated and the stationary background noise conditions as more effortful compared with the quiet background condition. This indicates a noise-related effect for the subjective ratings of listening effort.

Auditory-sensory processing

One aim of the study was to compare noise-related modulation of ERPs between CI users and NH listeners. The amplitude of both the N1 and P2 ERPs was largest in the quiet condition and decreased with stationary and modulated background noise in both groups. Additionally, the N1 latency was prolonged from quiet background, over stationary noise, to modulated noise. Similar results have been reported previously for NH listeners (Bennett et al., 2012; Billings et al., 2009, 2011). Our findings extend these reports by showing noise-related prolongation of the N1 latency in CI users as well. This result confirms and extends the usefulness of the N1-P2 complex as a tool to better understand the impact of background noise on speech processing in individuals with or without hearing loss (Billings et al., 2011; Obleser and Kotz, 2011).

Our results show that the N1 latency of CI users was prolonged in quiet but not in noise when compared with NH listeners. This indicates a weaker modulation of the N1 latency in CI users as a function of background noise. The reduced modulation of the N1 latency in CI users may originate from a poor quality of the speech signal provided not only for noisy but also for quiet background conditions. Due to the general stimulus degradation, speech encoding for quiet and noisy background conditions seems to be more similar in CI users when compared with NH listeners. By contrast, in NH listeners the quality of speech in quiet is remarkably higher than for speech in background noise, and initial processing of speech sounds is shortened specifically for the easy listening condition in these individuals.

Importantly, we also found a relationship between the N1 latency and the speech intelligibility scores, indicating that faster auditory-sensory processing of words is associated with enhanced speech recognition ability with the CI (see the section "On the relationship between central auditory processing, verbal abilities and speech intelligibility" for the discussion of this relationship). However, one has to keep in mind that the N1 reflects the early-level sensory processing of auditory stimuli, while the performance in speech intelligibility tests reflects the combined effects of different sensory and cognitive processes. Nevertheless, an association between auditory cortex activity at N1 latency and speech intelligibility in CI users has been observed previously (Sandmann et al., 2015). Our results are consistent with the view that a more efficient processing of speech at lower-level processing stages is a good precondition for better speech intelligibility in different background conditions.

Lexical and semantic speech processing

The second aim of the study was to investigate higher-order processing that underlies speech recognition in CI users. Consistent with our hypothesis, we found longer latencies for both the N2 and the P3 ERP in CI users than in NH listeners. However, the latencies of our peaks were rather late when compared with other studies using the oddball paradigm (Beynon et al., 2005; Henkin et al., 2009). It is highly likely that this discrepancy between previous findings and the present results is related to the different types of the presented stimuli (vowels, syllables vs. words).

Similar to our study, N2 latencies around 400 – 500 ms have been reported previously for NH listeners who were tested in a comparable paradigm with ecologically valid stimuli (Deacon et al., 1991; Schmitt et al., 2000). In order to further approach everyday listening conditions, the present study used different words instead of two words or syllables. This enforced the participants to fully retrieve the words' meaning from their mental lexicon. This process may be reflected by the N4 component (Brink and Hagoort, 2004; van den Brink et al., 2001; Deacon et al., 1991; Polich, 1985; Wang and Dong, 2013). However, differentiating the N2 clearly from the N4 is not trivial, and previous studies have shown contradicting results (Brink and Hagoort, 2004; van den Brink et al., 2001; Deacon et al., 1991; Polich, 1985; Wang and Dong, 2013). Some studies have found the two components being clearly distinguishable from each other (van den Brink et al., 2001; Deacon et al., 1991). By contrast, other studies have suggested that the N2 is not distinct from the N4 or that the N4 is even likely to be a generic N2 (Brink and Hagoort, 2004; Polich, 1985). With our present data we cannot establish whether the late negativity (what we have been naming the N2) is a neat N2 or an N4 component. For the interpretation of our results this does not matter however: the group differences found for the N2/N4 component in the present study point to a slowed lexical information access and semantic processing in CI users compared with NH listeners.

It is likely that the slow-down of the N2/N4 latency is related to the limited CI input which only partially matches to the attributes stored in the long-term memory (lexical representation), requiring additional explicit processing of the (limited) information transmitted by the CI (Finke et al., 2015; Rönnberg et al., 2013). One may speculate that in noisy background conditions the N2/N4 latency is further prolonged, given that the mismatch between the CI input and the cortical representation would be enhanced in difficult listening conditions. Indeed, we found that CI users showed noise-related prolongation of the N2/N4 latency, suggesting more difficulties in lexical information access in conditions with background noise. Similarly, prolonged N2 latency has been previously observed for lower SNRs in NH children, indicating that adverse listening conditions lead to delayed N2 latency (Almeqbel and McMahon, 2015).

Consistent with the P3 latencies, RTs were delayed in CI users compared with NH listeners suggesting longer word processing time in these individuals. Further, our results are in line with previous studies which reported prolonged P3 latency in CI users to simple speech stimuli (vowels and syllables; (Beynon et al., 2005; Soshi et al., 2014) and to words presented in the context of an auditory Stroop task (Henkin et al., 2014). Given that the P3 deflection may reflect stimulus evaluation (Donchin and Coles, 1998; Polich, 2007), our results indicate slowed classification between target and nontarget words in CI users when compared with NH listeners. Importantly, lexical categorization can only be completed after the acoustic-phonetic features of the words are mapped to lexical representations. Correspondingly, in our study we observed a delay in CI users not only for lexical information access (reflected by N2/N4 latency) but also for the word classification process (reflected by P3 latency).

Together with the finding of higher ratings of listening effort, prolonged N2/N4 and P3 latencies indicate that CI users experience difficulties during speech perception, even in quiet listening conditions. This conclusion is confirmed by the positive correlation between the N2/N4 latency and the ratings of the listening effort. In summary, the N2/N4 results support the view that the limited quality of the CI input leads to prolonged neural processing of speech, more effortful listening, and higher susceptibility to noisy background conditions (Finke et al., 2015; Hochmair-Desoyer et al., 1997; Rönnberg et al., 2013; Zeng et al., 2011).

On the relationship between central auditory processing, verbal abilities and speech intelligibility

Previous studies with NH listeners, hearing aid and CI users emphasized the important role of the WM capacity and verbal abilities for speech intelligibility (Akeroyd, 2008; Benard et al., 2014; Kronenberger et al., 2013a, 2013b; Rönnberg et al., 2013).

We used the MWT-B to test lexical recognition and found that CI users performed significantly worse than NH listeners. However, we found no relationship between lexical recognition ability and the individual CI outcome. This is in contrast to a study with NH listeners which reported a positive relationship between the lexical recognition (MWT-B) and speech intelligibility in challenging listening conditions (Carroll et al., 2015). It is likely that the discrepancy in results is related to variations in methodology, in particular in terms of the used speech material, the task difficulty and the characteristics of the participants (e.g. age, hearing threshold in the two ears).

Interestingly, we found that speech intelligibility correlated with the lexical fluency as well as with the verbal WM capacity in the group of CI users. This goes in line with the Ease of Language Understanding (ELU) model by Rönnberg and colleagues (Rönnberg et al., 2013). According to this model, WM capacity is needed to support speech understanding via an explicit processing loop in challenging listening conditions, such as listening via a CI. The observed relationship between CI outcome, verbal working memory and lexical abilities supports the view that auditory cognition plays an important role for speech intelligibility in CI users.

Our results revealed that latencies of both perceptual and higher-order processes were associated with speech recognition ability in CI users. Specifically, shorter N1 and N2 latencies correlated with higher speech intelligibility scores. Our findings confirm previous work which showed an association between ERPs at auditory-sensory processing stages and speech intelligibility with the CI (Sandmann et al., 2010, 2015).

The correlation analyses revealed a relationship between subjective ratings of listening effort and the N2/N4 latencies in CI users but not in NH listeners. Specifically, higher listening effort ratings were associated with prolonged N2/N4 latencies, suggesting that lower listening effort is associated with faster mapping of acoustic-phonetic features to lexical representations. Interestingly, these relationships were found specifically for each background condition (**Figure 6**), confirming a direct relationship between listening effort and access to lexical information stored in the long-term memory.

5. Summary and conclusions

The present study examined the relationship between cortical processing of words, cognitive abilities, and speech intelligibility in postlingually deafened CI users. Our results revealed poorer speech intelligibility in CI users than in NH listeners and group-specific modulation effects of ERPs as a function of background noise. While NH listeners showed stronger noise-related modulation of the N1 latency, CI users revealed enhanced modulation effects of the N2/N4 latency. In general, higher-order processing (N2/N4, P3) was prolonged in CI users when compared with NH listeners. These results suggest that CI users and NH listeners differ with regards to both the sensory and the higher-order processing of speech in quiet as well as in noisy background conditions. CI users show slower access to lexical information and prolonged word evaluation. It is likely that the perception difficulties observed in CI users are caused by a mismatch between the limited CI input and the word representation stored in the long-term memory (Rönnberg et al., 2013). In the presence of background noise, this mismatch is further enhanced, and more effortful processing of the degraded speech sound from the implant is required.

The present study provides evidence for complex interplays between speech intelligibility, neuronal processing, verbal abilities, verbal working memory and subjective ratings of listening effort in CI users. Although our results were obtained from postlingually deafened adult CI users, it is likely that similar relationships can be observed in prelingually deaf adult CI users. Previous work has reported that verbal abilities and executive functions relate to CI outcome in prelingually deaf children (Kronenberger et al., 2013a, 2014). Together with our results, these findings underline the important role of auditory cognition for speech intelligibility in CI users. Specific cognitive abilities may help to compensate for the degraded auditory input. Despite being of clinical relevance, cognitive factors are currently hardly considered in the clinic. Our results indicate that differences in auditory amd cognitive processing contribute to the variability observed in CI users. In the long-term, the better understanding of individual factors and their interplay may help predict the CI outcome and might contribute to the further improvement of auditory rehabilitation with the CI.

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Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Figure legends:

Figure 1: Experimental design of the oddball task in the three background conditions (quiet, stationary CCITT noise, modulated ICRA5 noise shown from top to bottom).

Figure 2: CI users responded slower **(A)** and less accurate compared to NH listeners **(B)**. **C.** shows the subjective ratings of listening effort which were overall higher in CI users compared to NH listeners. CI users are plotted in dark grey, NH listeners in light grey.

Figure 3: ERPs at frontocentral scalp regions. Left: The figure shows the N1 and P2 ERPs (average across all channels in the region-of-interest) for the three different background conditions for NH listeners and CI users. The voltage maps at N1 and P2 latency are given for the grand averages computed across all conditions. Right: The bar plots show the noise-related modulation of N1 and P2 amplitudes and latency measures. The N1 latency shows group specific modulations of background noise. All bar plots show the means ± 1 standard error of the mean.

Figure 4: ERPs at central scalp regions. Left: The figure shows the N2 ERPs (average across all channels in the region-of-interest) for the three different background conditions separately for NH listeners and CI users. The voltage maps at N2 latency are given for the grand averages computed across all conditions. Right: The bar plots show the increased N2 latencies for CI users compared to NH listeners. In CI users (but not in NH listeners) the N2 latencies are enhanced in background noise compared to the quiet condition. Both bar plots show the means ± 1 standard error of the mean.

Figure 5: ERPs at parietal scalp regions. Left: The figure shows the ERPs (average across all channels in the region-of-interest) separately for targets and nontargets, averaged across the three background conditions. Note the two vertical lines representing the onset (0 ms) and the offset (800 ms) of the auditory stimulus. The late ERPs evoked to the *onset* of the stimuli (P3 peak) and ERPs evoked to the *offset* of the stimuli (N1 and P2 peak) partly overlapped, at least in CI users who showed prolonged higher-order processing. This was the reason for computing the target-minus-nontarget difference waves which allowed the subtraction of the overlapping offset response from the onset response. The P3 analysis was performed on these difference waves computed for each background condition and group. The voltage maps at P3 latency are given for the grand averages computed across all conditions. Right: The bar plots show the results from the peak detection analysis. The P3 latencies were significantly prolonged in CI uses compared to NH listeners across all background conditions. Area

amplitude and area latency measures are given for each condition. Both bar plots show the means ± 1 standard error of the mean.

Figure 6: Results from the correlation analyses. Top: Correlations of speech test scores with N2 latencies in quiet **(A)** and noise **(B)** as well as correlations between N1 latencies and verbal working memory **(C)** and speech test scores in the monosyllabic word test **(D)**. Bottom: **E-G** show the rank correlations of N2 latencies and subjective listening effort for each of the three background condition (quiet, stationary, modulated from left to right).

Table 1: Participant demographics. Speech perception scores for the second CI are given in parentheses. Low frequency loss is calculated as the average over 125, 250, and 500 Hz and high frequency hearing loss as the average over 1, 2, and 4 kHz. EAS is the abbreviation for Electric-Acoustic Stimulation (combination of cochlear implant and hearing aid within one device).

ID	Age	Tested site	Strategy	Implant	Course of hearing loss	HSM in quiet [%]	HSM in noise [%]	Monosyllables [%]	CI use [month]	2nd CI use [month]	Hearing loss low Freq	Hearing loss high freq
CI 01	45	left	FS4	FLEX 28	progressive	100 (100)	74 (-)	80 (85)	14	39	(-)	(-)
CI 02	63	left	FS4	FLEX 20	progressive	52	22	30	26	Hearing aid	40	85
CI 05	55	left	FS4	FLEX 28	progressive	92 (31)	21 (0)	35 (25)	27	40	(-)	(-)
CI 06	59	right	FS4	FLEX 28	progressive	100 (-)	80 (53)	55 (45)	17	30	(-)	(-)
CI 07	73	left	FS4	FLEX 28	progressive	89	42	50	21	Hearing aid	83	78
CI 08	75	left	FS4	FLEX 28	progressive	78	20	25	27	Hearing aid	32	48
CI 09	62	left	FSP	FLEX 28	progressive	70	27	45	21	Hearing aid	62	110
CI 10	66	right	FSP	FLEX 28	progressive	100	75	70	18	Hearing aid	15	43
CI 11	48	left	FSP	FLEX 20	progressive	100	76	75	48	Hearing aid	73	73
CI 12	43	left	FSP	FLEX 20	progressive	100 (100)	66 (48)	60 (55)	58	52 (EAS)	(-)	(-)
CI	6	left	FSP	FLEX	progre	92	62	65	47	Hearin	48	100

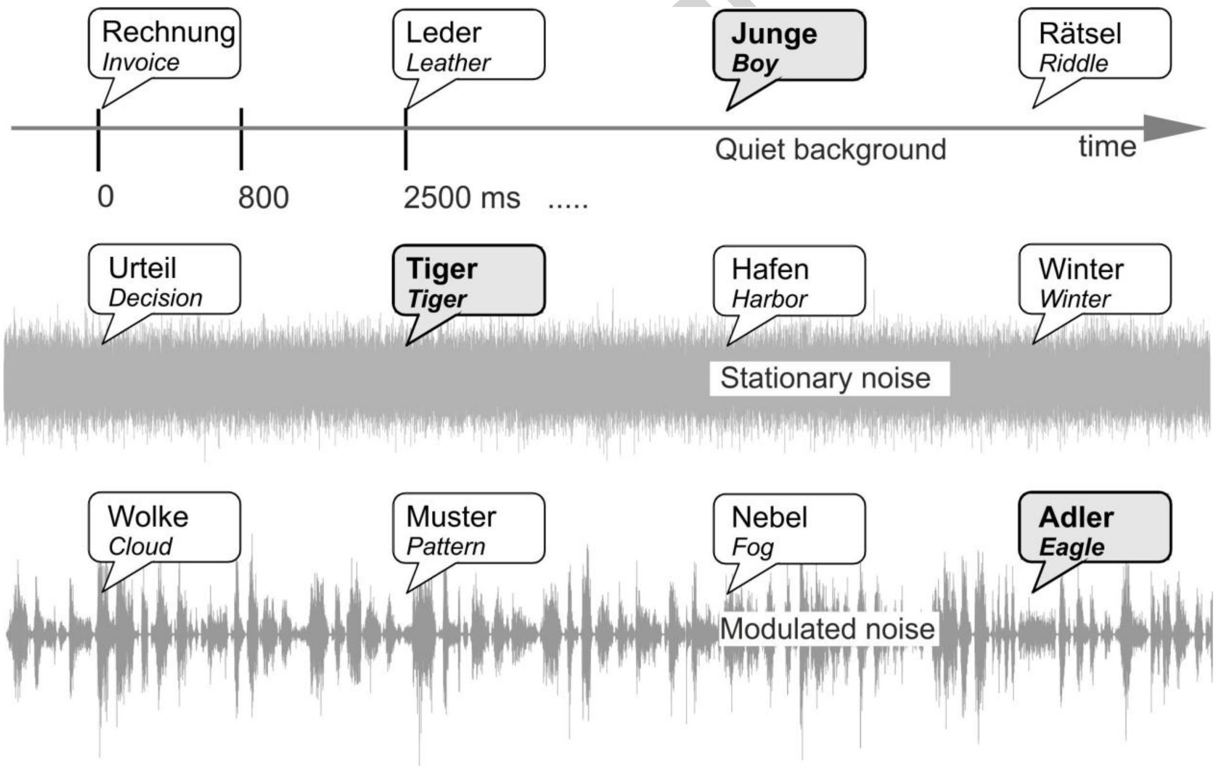
13	3			20	ssive					g aid		
CI	6			FLEX	progre	86	51					
14	2	left	FS4	20	ssive	(100)	(88)	45 (85)	20	35	(-)	(-)
CI	6			FLEX	progre					Hearin		
15	6	left	FS4	20	ssive	100	51	60	55	g aid	55	108

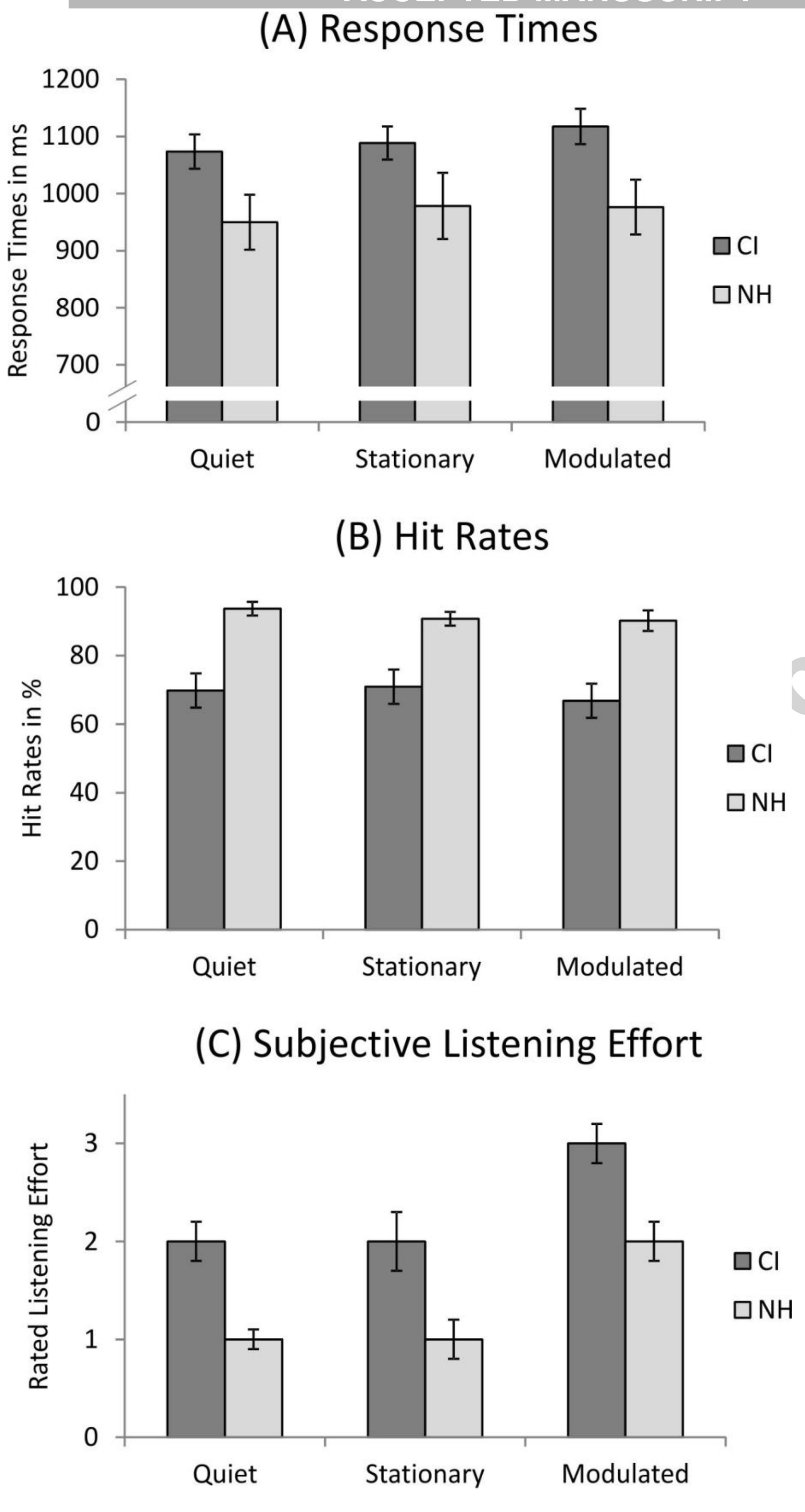
Table 2: Overview over the statistical results

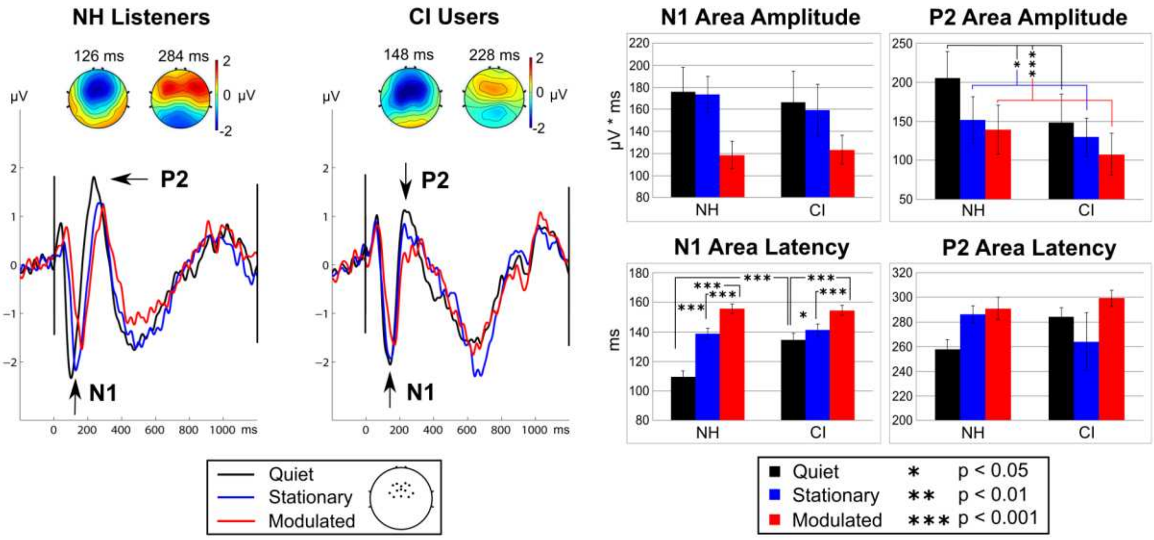
Table 3: Quantification of the N2 waveform.

Highlights:

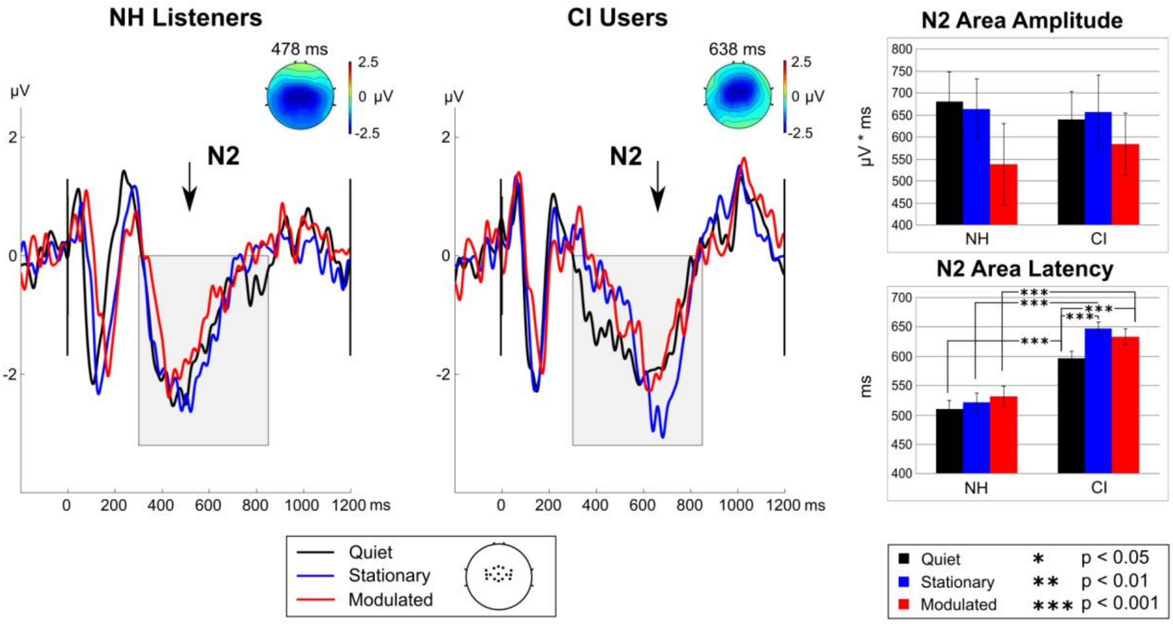
- Group-specific modulation effects of ERPs as a function of background noise
- NH listeners showed stronger noise-related modulation of the N1 latency
- CI users revealed enhanced modulation effects of the N2 latency
- Postperceptual processing was prolonged in CI users when compared with NH listeners
- Speech processing and speech intelligibility in CI users is related to verbal abilities



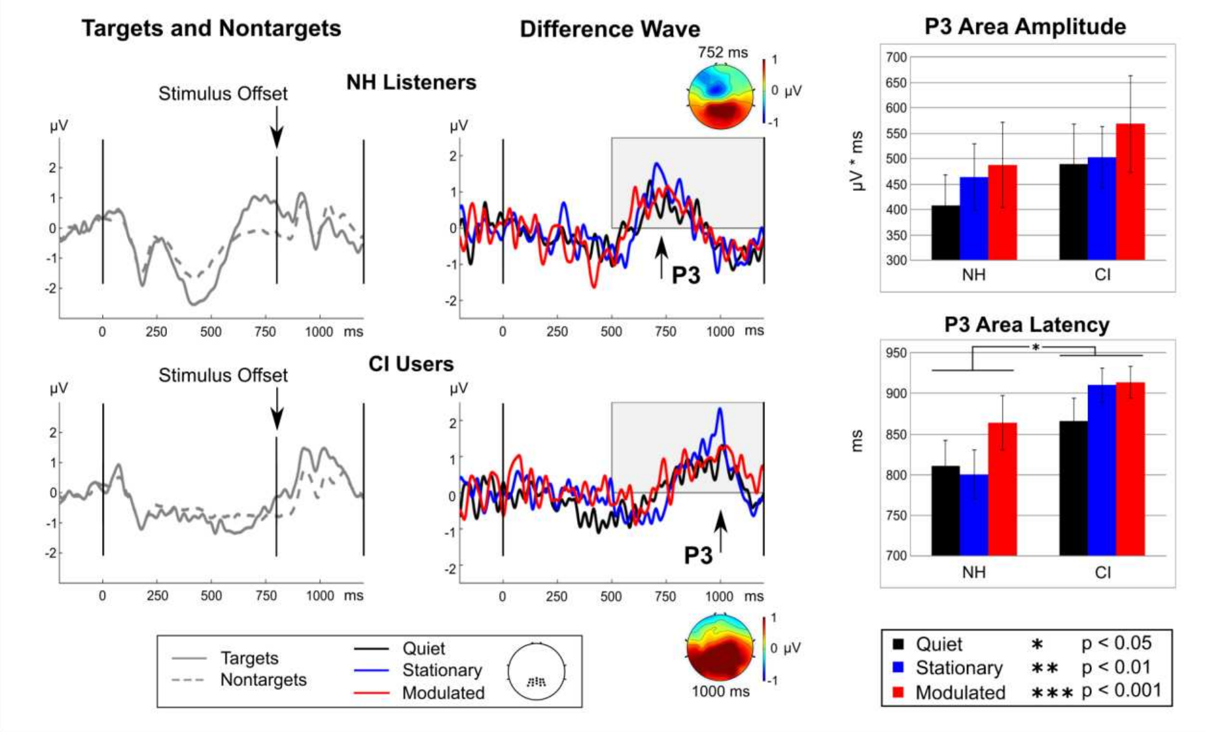

(A) Response Times
Response Times in ms
1200
1100
1000
900
800
700
0
Quiet
Stationary
Modulated
CI
NH
(B) Hit Rates
Hit Rates in %
100
80
60
40
20
0
Quiet
Stationary
Modulated
CI
NH
(C) Subjective Listening Effort
Rated Listening Effort
3
2
1
0
Quiet
Stationary
Modulated
CI
NH



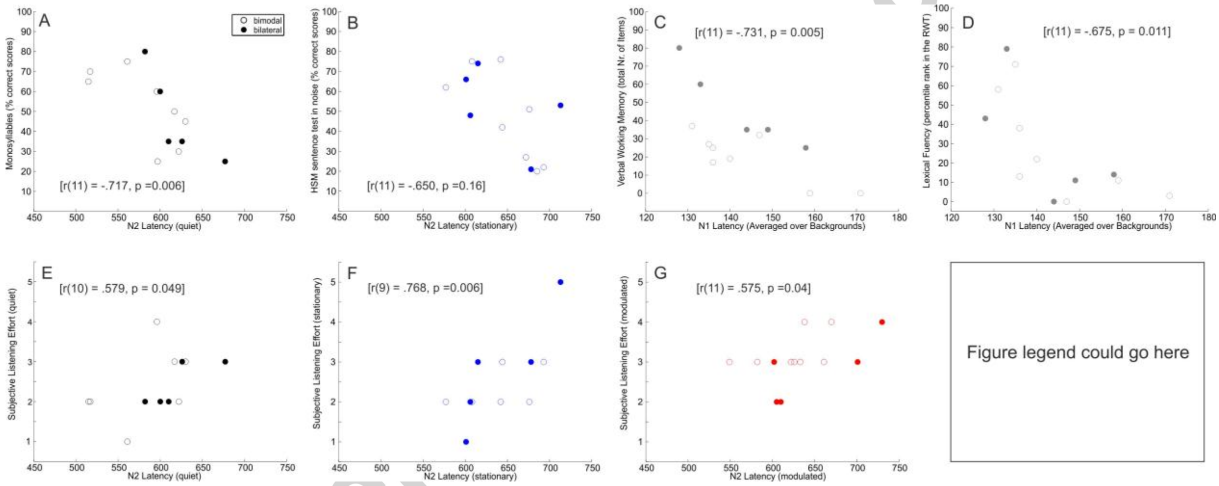
NH Listeners
CI Users
126 ms
284 ms
148 ms
228 ms
µV
P2
N1
Quiet
Stationary
Modulated
N1 Area Amplitude
P2 Area Amplitude
N1 Area Latency
P2 Area Latency
µV * ms
ms
NH
CI
* p < 0.05
** p < 0.01
*** p < 0.001



NH Listeners
CI Users
478 ms
638 ms
µV
N2
Quiet
Stationary
Modulated
N2 Area Amplitude
N2 Area Latency
µV * ms
ms
NH
CI
* p < 0.05
** p < 0.01
*** p < 0.001



Targets and Nontargets
Difference Wave
P3 Area Amplitude
NH Listeners
CI Users
Stimulus Offset
P3
752 ms
1000 ms
µV
ms
µV * ms
NH
CI
P3 Area Latency
Targets
Nontargets
Quiet
Stationary
Modulated
* p < 0.05
** p < 0.01
*** p < 0.001



A
[r(11) = -.717, p =0.006]
bimodal
bilateral
Monosyllables (% correct scores)
N2 Latency (quiet)
B
[r(11) = -.650, p =0.16]
HSM sentence test in noise (% correct scores)
N2 Latency (stationary)
C
[r(11) = -.731, p = 0.005]
Verbal Working Memory (total Nr. of Items)
N1 Latency (Averaged over Backgrounds)
D
[r(11) = -.675, p = 0.011]
Lexical Fluency (percentile rank in the RWT)
N1 Latency (Averaged over Backgrounds)
E
[r(10) = .579, p = 0.049]
Subjective Listening Effort (quiet)
N2 Latency (quiet)
F
[r(9) = .768, p =0.006]
Subjective Listening Effort (stationary)
N2 Latency (stationary)
G
[r(11) = .575, p =0.04]
Subjective Listening Effort (modulated)
N2 Latency (modulated)
Figure legend could go here